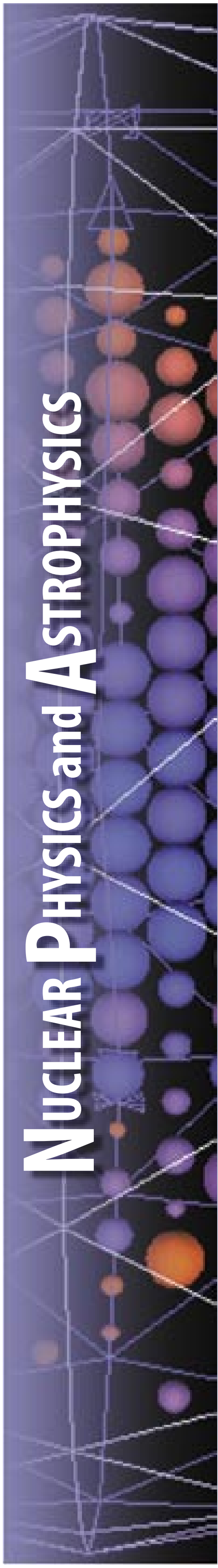

Accelerator Neutrino Experiments on the LSND and MiniBooNE

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The neutrino is one of the most elusive particles in the universe, yet it exists in great abundance and is a fundamental element in the universe's subatomic structure. Because these low-energy particles interact weakly with other particles, neutrinos had defied detection for years until 1953 when LANL scientists Fredrick Reines (Figure 1) and Clyde Cowan, Jr., detected these elusive particles in experiments that used liquid scintillator detectors at reactors in Washington and South Carolina. The neutrino, originally thought to be massless, exists in three distinct states (commonly called "flavors")—electron, muon, and tau forms.

LANL researchers used the LSND[1] from 1993–1998 to conduct experiments designed to collect data and obtain evidence that neutrinos oscillate from the muon neutrino form into the electron neutrino form. Neutrino oscillations are the transformation of one neutrino flavor into another neutrino flavor, and these transformations occur only if neutrinos have mass and if there is mixing among the neutrino flavors. The LSND results imply that neutrinos constitute at least 1% of the universe's total mass. MiniBooNE,[2] which is now operational at FNAL in Illinois, is the first phase of the larger BooNE that will definitively test the LSND evidence for neutrino oscillations and precisely measure the oscillation parameters. MiniBooNE is looking for oscillations of muon neutrinos (ν_μ) into electron neutrinos (ν_e). A large tank filled with mineral oil (CH_2) is used to look for particles produced when neutrinos hit the nuclei of the atoms that make up the oil. The signature of such an interaction is a cone of light, known as Cerenkov light, which hits light-sensitive devices (PMTs) mounted on the inside surface of the tank. If successful, MiniBooNE will provide a unique environment to observe physics beyond the Standard Model.

Figure 1. Fred Reines working on an underground neutrino experiment at a South African mine in 1966 (photo courtesy of the University of California, Irvine).

LSND—The Foundation for Future Neutrino Research

The LSND experiment was designed to search for oscillations of muon antineutrinos to electron antineutrinos ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) from positively charged muon (μ^+) decay at rest (DAR) with high sensitivity. (The LSND collaboration consisted of groups from eleven organizations, including LANL). Over the six-year running period from 1993–1998, the LANSCE accelerator delivered 28,896 C (~ 0.3 g) of protons to the production target. The resulting DAR neutrino fluxes were well understood because almost all detectable neutrinos arose from positively charged pion (π^+) or μ^+ decay.

The LSND was an 8.3-m-long, 5.7-m-diam cylindrical tank that contained 167 tons of mineral

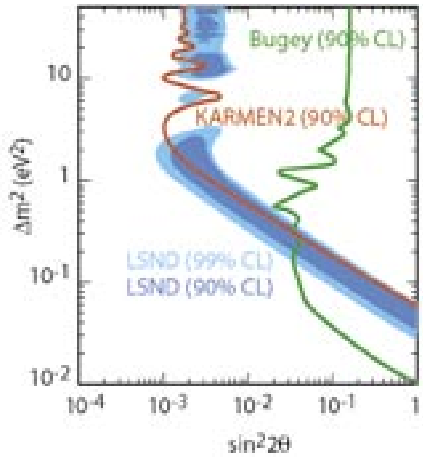

Figure 2. The ($\sin^2 2\theta$, Δm^2) oscillation parameter fit for the entire LSND data sample. (CL is "confidence level.")

oil with a dab of scintillating compound to amplify light signals used to reconstruct neutrino events. The Cerenkov light (described later) from these events was detected by 1,220 PMTs (each 8 in.) located on the inside surface of the LSND tank. The PMTs convert the light into electrical signals, which are gathered and interpreted by data-acquisition computers. The center of the LSND was 30 m from the neutrino source. The main veto shield consisted of a 15-cm layer of liquid scintillator in an external tank and 15-cm layer of lead in an internal tank. Designed to search for the presence of electron antineutrinos with great sensitivity, the LSND witnessed over 80 neutrino events that were consistent with muon antineutrinos oscillating into electron antineutrinos.

The primary neutrino-oscillation search in LSND was for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (i.e., a muon antineutrino to an electron antineutrino), where the $\bar{\nu}_\mu$ arise from DAR μ^+ in the beam stop, and the ν_e are identified through the reaction $\bar{\nu}_e p \rightarrow e^+ n$. This reaction allowed a two-fold signature of a positron with a 52.8-MeV endpoint and a correlated 2.2-MeV gamma ray (γ) from neutron capture on a free proton. More events were observed than expected, and the excess was consistent with neutrino oscillations.

Figure 2 shows the ($\sin^2 2\theta$, Δm^2) oscillation parameter fit for the entire data sample, $20 < E_e < 200$ MeV. The mixing angle between the two neutrinos is "$\sin^2 2\theta$," and the difference in masses squared of the two neutrinos is "Δm^2." The fit includes both $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillations and all known neutrino backgrounds. The inner and outer regions correspond to 90% and 99% confidence-level allowed regions, whereas the curves are 90% confidence-level limits from the Bugey reactor experiment and the KARMEN2 experiment at ISIS, the Rutherford-Appleton Laboratory Neutron Facility in the United Kingdom. The allowed region that is most favorable is the band from 0.2–2.0 eV^2, although a region around 7 eV^2 is also possible.

MiniBooNE—The First Phase for Confirmation of Neutrino Oscillations

The MiniBooNE detector consists of a 12-m-diam spherical tank contained within a cylindrical vault (Figure 3a and b). An inner tank supports 1,280 individual PMTs pointed inward and optically isolated from the tank's outer region, which contains an additional 240 PMTs (Figure 3c). The inner tank is filled with 800 tons of mineral oil, which is the equivalent of 44 tanker trucks filled with liquid. An outer tank serves as a veto shield for identifying particles both entering and exiting the detector. MiniBooNE is located ~ 500 m from FNAL's neutrino source, and it detects one neutrino collision every 20 s. For this first phase of the experiment, we expect to detect one million neutrino events per year.

In MiniBooNE, the 8-GeV protons from FNAL's Booster accelerator interact with the atoms in a beryllium target located inside a magnetic focusing horn (Figure 4). (The Booster accelerator can reliably deliver protons for most of a calendar year, which allows the experiment to receive up to ~ 5×10^{20} protons per year.) The positively charged

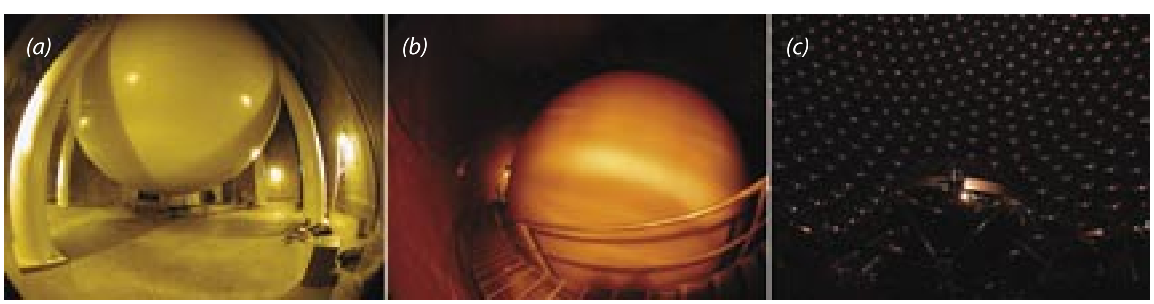

Figure 3. The MiniBooNE detector tank viewed from the floor (a) and from the stairway (b) in the underground vault. (c) A portion of the PMTs installed inside the detector.

Figure 4. FNAL's magnetic focusing horn. The beryllium target that produces pions through proton interactions with the target material is located in the upstream position inside the horn.

pions *(π)* produced from these interactions are focused by the magnet horn into a 2-m-diam, 50-m-long steel pipe where they decay into muon neutrinos *(ν_μ)*. At the end of the decay pipe, a concrete/steel absorber stops all particles except the muon neutrinos, which continue through ~ 450 m of earth to reach the detector tank. The muon neutrinos—delivered in bursts that last 1.6 millionths of second, 5 times per second—collide with carbon atoms in the mineral oil, producing muons *(μ^+)*. These subatomic charged particles create cones of Cerenkov light—a key factor in these experiments—as they travel through the mineral oil. (Cerenkov light is essentially the electromagnetic equivalent of a sonic boom. It travels to the edges of the detector tank where the PMTs receive the light and convert it to electrical signals.)

Some of the muon neutrinos entering the detector tank can oscillate into electron neutrinos *(ν_e) before* they collide with carbon atoms. If this occurs, electrons (instead of energetic muons) will be produced when the electron neutrinos collide with the carbon atoms in the mineral oil. The electrons scatter and quickly come to rest after colliding with atoms in the mineral oil. The subsequent Cerenkov cone of light is distinct (i.e., the inner and outer edges of the cone are hazy) from that produced by other interactions within the detector tank. If MiniBooNE verifies the LSND experiment, then approximately 1,000 $\nu_e C \to e^- X$ events should be observed above background from $\nu_\mu \to \mu_e$ oscillations. There are three main backgrounds to the oscillation search: (1) intrinsic ν_e background in the beam from μ and K (kaon) decay in the decay pipe, (2) misidentified μ events ($\nu_\mu C \to \mu^- X$), and (3) misidentified π^0 (pion) events ($\nu_\mu C \to \nu_\mu \pi^0 X$). Figure 5 shows the expected oscillation sensitivity for the two-year ν_μ or $\bar{\nu}_\mu$ run cycle.

The MiniBooNE detector and beam are now fully operational and taking data. The detector was calibrated with laser-calibration events; the energy scale and resolution were determined from cosmic-muon and Michel-electron events, and approximately 160,000 clean neutrino events were recorded after the first year of data taking with about 1.5×10^{20} protons on target. At present, the experiment is clearly reconstructing both $\nu_\mu C \to \mu^- X$ charged-current events and $\nu_\mu C \to \nu_\mu \pi^0 X$ neutral-current events, which are the two main backgrounds to the $\nu_\mu \to \nu_e$ oscillation search. As shown in Figure 5, π^0 events are being reconstructed at approximately the correct mass with a mass resolution of about 21 MeV.

The current plan is to run the first two full years (1×10^{21} protons on target) with ν_μ and then switch to a $\bar{\nu}_\mu$ run cycle. First results are expected by 2005, and if the LSND oscillation signal is confirmed, a BooNE detector will then be built at a different distance than the MiniBooNE detector to obtain the highest precision measurement of the oscillation parameters.

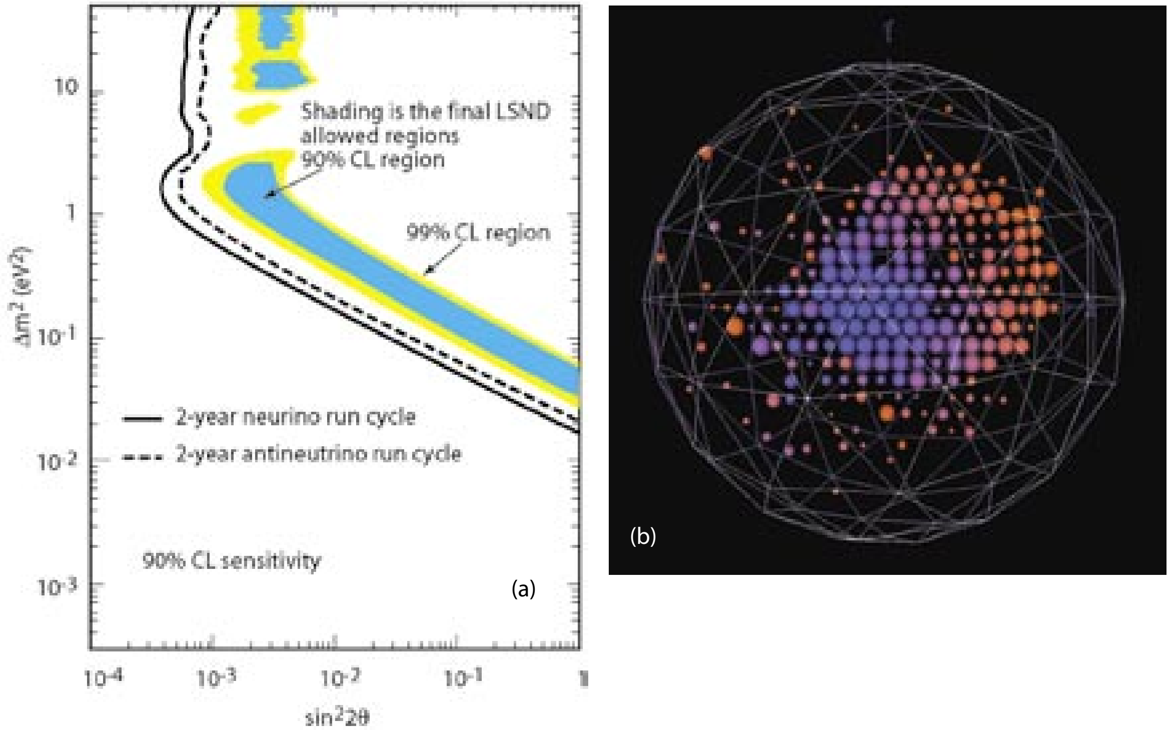

Figure 5. (a) The MiniBooNE expected oscillation sensitivity for a full two-year run cycle. (CL is "confidence level.") (b) A typical MiniBooNE neutrino-induced event. The colors relate to elapsed time; the blue represents early PMT hits and the orange represents later PMT hits. In this particular data event, there were less than 6 veto hits and over 200 tank hits.

Conclusion

The confirmation of neutrino oscillations at high Δm^2 would have a huge impact on astrophysics, as well as particle and nuclear physics. When combined with the evidence for neutrino oscillations from solar and atmospheric neutrino experiments, the present data seem to imply physics beyond the Standard Model, such as the existence of light, sterile neutrinos or the violation of CPT. (CPT is the combined operation of charge conjugation, parity inversion, and time reversal.) The MiniBooNE experiment at Fermilab will provide a definitive test of the LSND evidence for neutrino oscillations.

References

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